Descriptive fault trees for structural pavement failure mechanisms

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Descriptive Fault Trees for Structural Pavement Failure Mechanisms

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Abstract:

Unplanned structural road pavement failures may increase maintenance expenditure for Road Controlling Authorities from that estimated in budgets. To deal with this effectively, road asset managers who are faced with the complex task of forecasting and planning maintenance with fixed and constrained budgets, or operating road networks with high risk profiles, need to understand the factors affecting road pavement failure. With such knowledge presented graphically in fault trees road asset managers can diagnose pavement failures correctly, recognise symptomatic problems across road networks, and forecast effective maintenance to preserve the network's structural integrity.

This paper develops three fault trees for rutting, load associated fatigue cracking, and shear failure. A methodology is described which can be used by asset managers in conjunction with the fault trees to correctly diagnose the mode(s) of pavement failure and the associated cause(s). A case study using New Zealand road network data demonstrates how engineering knowledge can improve on the predictive power of computational models during the initial stages of model development.

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INTRODUCTION

Road asset managers have the important task of making the best possible use of maintenance funds to ensure the road network remains functional for the user and it's structural integrity is protected. As funding is often insufficient for the needs of the network, it is imperative to prevent early pavement failure using appropriate maintenance strategies, which are preventative rather than reactive in nature. However, without a comprehensive understanding of failure, pavement failures are often misdiagnosed which leads to inappropriate maintenance (Schlotjes et al., 2009). Maintenance strategies can be aided by using pavement performance models that predict the structural deterioration of road pavements. However, the majority of these models focus on singular modes of failure, have a mechanistic design, and do not include diagnostic capabilities (Schlotjes et al., 2011).

The formulation of pavement deterioration or performance models also require an in-depth understanding of the complexities of pavement failure, and this in turn can assist in selecting appropriate model variables (Isa et al., 2005). Whilst a number of researchers have developed approaches for infrastructure systems which utilise an understanding of failure modes such as fault trees (Xiao et al., 2011; Patev et al., 2005; Pickard et al., 2005), this practice is not widely used in the road sector.

A methodology to address this was designed to develop three descriptive fault trees for rutting, fatigue cracking, and shear pavement failure. The fault trees, and therefore this comprehensive understanding of these pavement failure mechanisms, were further used to infer engineering knowledge into computational models to improve the predictive results of modelling techniques (Schlotjes, 2013). This paper demonstrates the importance of incorporating engineering knowledge when modelling pavement performance and focuses on:

1. The methodology followed in this research to design descriptive fault trees for structural pavement failure;
2. The development of three fault trees (or failure charts, used interchangeably from herein) for rutting, fatigue cracking, and shear failure, depicting a number of causes of each failure mechanisms;
3. The use of the developed failure charts in other research applications, such as modelling pavement performance, and
4. The benefit this approach has in both project level and network level decision making.

A case study is presented to demonstrate the approach using network data. Typical New Zealand roads are the focus of this case study, the majority of which consist of thin flexible, unbound granular, chip-sealed pavements that carry less than 10,000 vehicles per day (Hayward, 2006), and herein are classified as low volume roads. The main structural failure modes prevalent on these pavements are rutting, cracking and shear failure (Henning et al., 2009; Gribble & Patrick, 2008).

ROAD PAVEMENT FAILURE MECHANISMS

The three failure modes of interest on flexible, unbound granular, chip-seal pavements are:

1) Rutting failure which appears on the pavement as depressions in the wheelpath and those on the outside wheelpath are the most severe (Schlotjes et al., 2009). It’s primary cause is associated with the movement of the materials in the lower layers, under traffic loading (Papagiannakis, 2008; Martin, 2008), due to the densification of materials or the shear flow of materials beneath the wheelpaths. Rutting can also be caused by the use of weak materials, inadequate design, or faults in the layers of the pavement as a result of poor construction. Rutting is an indication of the deterioration of the structural

integrity of the pavement to adequately dissipate the stresses induced by traffic. In addition, ruts can allow water to pond on the road surfacing posing hazards of black ice formation and vehicle aquaplaning.

2) Inter-connected polygonal patterns on the pavement surface are the main indicator of fatigue (structural) cracking failure. Other types of cracking failure exist on flexible pavements, however these failure types are beyond the scope of this paper and will not be discussed further. Load associated fatigue cracking occurs as a result of excessive strain caused by excessive traffic loading or load repetitions, or unbalanced pavement layers (e.g. stiff upper layers with poor pavement support), or brittle surface materials either from aging or inadequate materials (Henning et al., 2006; Martin, 2008). The main concern with cracking is that it permits water to enter the lower layers of the pavement. Additionally, cracking may in time worsen ride quality with an associated increase in road user costs.

3) Shear failure, primarily seen as shoving or edge breaks and occasionally as a secondary effect of potholes, is generally attributed to inadequate or weakened material in the road pavement (layers), or insufficient shoulder support, or material shear on the pavement edge. Because this failure mechanism is not necessarily related to traffic loading on low volume roads, although traffic loadings can further exacerbate shear failures, the defects manifest outside of the wheelpaths (Schlotjes et al., 2011). As with cracking, shear related failures allow water to enter the pavement structure and can worsen the ride quality.

UNDERSTANDING PAVEMENT FAILURE

The interaction of failure factors and associated failure mechanisms makes the task of predicting the occurrence and diagnosing the correct mode of failure challenging and can often result in one or more failure mechanisms being overlooked. Consequently, the selected maintenance treatment may not always address the underlying cause(s) of failure (Schlotjes et al., 2009). Therefore, a comprehensive understanding of failure is required to identify and diagnose the cause(s) of failure so timely and appropriate maintenance can be applied.

To address this, a methodology was developed which was based on Failure Mode and Effect Analysis (FMEA) and Fault Tree Analysis (FTA) (Xiao et al., 2011; Pickard et al., 2006; Seyed-Hosseini et al., 2006; Patev et al., 2005). The former is an analytical tool for reliability analysis, developed in the 1960's, which can be used to identify possible failure causes to minimise or eliminate failure in their systems. By using a weighting and ranking system, each event (failure) is assigned a priority (risk) number that assesses the overall impact of the event. FTA on the other hand presents a graphical representation of the causes involved in failure and enables concurrently occurring failure factors to be included in the representation of failure. The graphical format shows a breakdown of the critical paths leading to failure, and from this, the failure paths can be deduced.

Both of the above techniques recognise the importance of identifying the causes of failure and generating a graphical representation of the interactions between the possible failure causes. This research expands the fundamentals of these techniques to include a consideration of multiple failure factors and the identification of failure paths. Accordingly engineering knowledge was used to develop three failure charts, or fault trees, which can be used to determine the causes of rutting, cracking and shear failure. The application of these trees can aid in:

- Identifying and selecting the influential factors which are associated with a particular type of road pavement failure;
- Assisting the development of road pavement deterioration models to improve the predictive performance of the modelling technique, and

- Diagnosing the underlying cause(s) of failure, and subsequently the correct failure mode, to assist the road asset manager in selecting appropriate road maintenance.

FIGURE 1 outlines the use of the failure charts, and subsequently the understanding of failure, in practice. The methodology consists of several steps. Firstly, the influential failure factors are identified. This step is supported by the input of the respective dataset to ensure the availability of factors within the target network dataset. From the modelling process and model outputs, the failure understanding and dataset can be revisited to determine the factors contributing to failure (the failure path) for individual sites, and subsequently diagnose the cause(s) of failure.

Flexible Pavement Failure Paths

Individual failure charts were developed for each of the three failure mechanisms for the road pavements in the New Zealand dataset using the following sources of information.

i) Literature Review:

   The literature search focused on the predominant failures of New Zealand's road network. The review of the literature identified the fundamental factors involved in each of the rutting, cracking and shear failure modes.

ii) Data Analysis:

   Two independent datasets specific to New Zealand were analysed to identify influential failure factors and inter-relationships in the data, as well as confirming well recognised factors from the literature. Understanding such inter-relationships can be crucial in correctly diagnosing pavement failure and specifying the correct maintenance treatments as it is common for multiple factors to be associated with a particular failure mode (Schlotjes et al., 2011). This paper assumed each failure mode to act independently of each other; however, Schlotjes (2013) and Schlotjes et al. (2013) explore in detail the interdependency of these failure mechanisms.

iii) Expert Opinion:

Knowledge was elicited from those who have managed road networks throughout New Zealand for many years. This provided additional insight into the causes of, and factors influencing, failure. This knowledge proved especially useful in identifying interactions between failure factors and interdependence of each failure type. The latter was considered beyond the scope of this paper; details on the interdependency of the failure mechanisms have been reported in concurrent publications (Schlotjes, 2013; Schlotjes et al., 2013).

The information accumulated from the three sources was collated into three failure charts, shown in FIGURE 2 to FIGURE 4, as described below. The presentation of this engineering knowledge of failure, and causative factors, is sequential.

Rutting:

Rutting failure occurs as a result of either plastic deformation or excessive strain (FIGURE 2). The factors associated with these issues are pavement composition and traffic respectively. Furthermore, deformation is due to plastic settlement in the underlying layers, which stems from poor materials, water ingress, or inadequate pavement design. Excessive strain is associated with fatigue failure and can result from a combination of poor pavement structure and traffic loading, most often excessive load repetitions where the cumulative number of standard axle loads has exceeded the design.

Fatigue Cracking:

Fatigue cracking is a result of (i) excessive repetitions of strain causing cracks in the structural layers of the pavement to propagate to the surface of the pavement; (ii) stiff upper layer causing unbalanced layers throughout the pavement; or, (iii) the use of inadequate surface materials, which may also become brittle over time (FIGURE 3). Excessive repetitions of strain occur when the layers in the road pavement are thinner or weaker than designed for (inadequate support for the pavement) and the cumulative repetitions of traffic loading are greater than those designed for. Poor pavement support is due to a weak underlying layer, often the subgrade (subgrade sensitivity). It should be noted that whilst it is recognised that the failure of the surface materials may not directly result in structural failure, it has been included here for completeness.

Shear:

Shear failure on New Zealand low volume roads is generally associated with material properties often exacerbated under vehicular loads, as opposed to only traffic and / or environmental factors (Transit New Zealand, 2000). The common causes of shear failure (FIGURE 4) include weak materials which were either weak initially or have weakened over their life, material shear or poor material properties, or inadequate structural (shoulder) support.

From the above analysis, five main groups of factors (traffic, composition, strength, environment, and subgrade sensitivity) which are most influential in affecting the three failure types studied in this paper, were identified and are summarised in TABLE 1. In addition, surface condition, which although it is a symptom rather than a cause of failure, is also included in TABLE 1 as it is regarded as an important parameter in modelling pavement performance and failure (Henning, 2008). This is recognised as a limitation of the model as not all surface symptoms are related to structural failure yet because of the nature of condition reporting such factor will best inform the model of likely structural failures. TABLE 1 presents a large number of independent variables, which can compromise the robustness of the model; however these variables are listed due to their involvement in failure.

Generic Failure Paths

Based on the analysis above, FIGURE 5 presents a generic failure chart which can be used to aid in the development of similar failure charts, and subsequently assist in diagnosing failure, for other pavement types. It includes the five main groups of factors described above and summarised in TABLE 1. The underlying concept considered is that failure can be due to poor support (bearing capacity) or that the loads which the structure is subject to, exceeds the design load (loading demand).

Under the bearing capacity failure, failure can be due to insufficient design, poor construction quality, environmental factors, or problems with the subgrade or foundations – factors relating to the pavement structure or its environment, excluding any type of loading. On the other hand, under the loading demand factor, failure can be due to solely excessive traffic or environmental loading, or a combined event involving traffic, such as excessive traffic loading on a poorly designed structure.

LONG-TERM PAVEMENT PERFORMANCE MODELLING

Knowledge surrounding pavement failure is extensive; presenting this information in fault trees not only focuses computational models on common failure paths for specific pavements and environments, but informs the model with engineering principles. The case study, focusing only on rutting failure, below demonstrates enhanced model results in predicting failure when engineering knowledge is considered in the early stages of the model design. Although the conceptual design of the model treats each failure mechanism as independent, the holistic approach taken recognises the interactions between failure factors.

The dataset was obtained from the Long-Term Pavement Performance (LTPP) data, collected from the State Highway network in New Zealand, and was selected because of its completeness and accuracy of the condition data (Henning et al., 2004). The dataset included only flexible chip-seal pavements with a traffic volume of 10,000 vehicles per day or less.

LTPP Data

The LTPP programme was established in New Zealand in 2000 with 63 test sites on the State Highway road network. Given the quantity of detailed inventory data and historical condition data, Henning (2008) demonstrated that the behaviour of road network could be modelled using the logistic regression modelling technique. In this research, failure was deduced from a combination of the inspection reports, maintenance history, and the failure limits for the condition data (e.g. rut depth > 20mm). In the context of this research, failure was defined as the time where maintenance was implemented when the pavement had reached the end of its service life.

The independent variables used in the modelling were identified with the help of the rutting failure chart (FIGURE 2) and TABLE 1. For example, rutting can be attributed to traffic factors. In the LTPP dataset, various measures of traffic were recorded and included AADT, HCVs, and ESAs, although the ESAs were dependent on the AADT and HCVs.

Logistic Regression Modelling

The logistic regression technique was selected to demonstrate the validity of the proposed approach. Previous research has shown that logistic regression models are comparative with other learning methods (Perlich et al., 2003). Linear techniques often face a limitation of fitting data to a linear curve, however when dealing with binary outcomes, the data rarely fits a linear curve; instead, they are more suited to a logistic regression S-shaped (sigmoid) function (Bergerud, 1996). Because of the nature of the New Zealand LTPP data, Henning (2008) successfully modelled pavement performance with this technique.

Using the six factor groups from TABLE 1, a total of 63 trials were completed on the rutting sub-dataset. Each trial was unique in that it contained a different number and combination of data factors.

The raw data was manipulated prior to modelling. The dependent variable, the failure output, was represented as a binary variable with 0 equating to a non-failure occurrence and 1 representing a failed pavement. For the purposes of demonstrating the methodology, the independent variables were normalised using a straight line transformation, thus assuming a normal distribution of the variable. Although this aspect is currently recognised as a limitation that requires further investigation, for the objectives of this paper, adopting this assumption was acceptable. A weighting factor was applied to the dataset, which resulted in equal importance for both the failed and non-failure sites.

The *glm()* function with the use of *family=binomial(link='logit')* in the *R* statistical package (Dalgaard, 2008; Faraway, 2006) was employed to model the data. A 10-fold cross-validation test was employed to ensure the variability of the predictions was accounted for in the results, and to ensure that the data used for training the model was not involved in the testing of the model.

The output of interest from the trialled logistic regression models (each of the 63 trials was modelled individually) was the misclassification error, which was used to evaluate the accuracy of the factor combinations and of the technique. This error is analogous to a positive predictive error (Petrie & Sabin, 2005), and defined as the percentage of misclassified road sections when the trained model attempts to predict the failure probability of the testing data. A misclassified site was defined as the predicted probability of failure, rounded to one or zero for simplicity of the comparison, was not equal to the actual failure.

The output, while it shows the effectiveness of the logistic regression technique, primarily demonstrates that certain combinations of the failure factor groups are the root causes of rutting failure.

Rutting Failure

TABLE 2 presents the ten combinations of failure factors (refer to TABLE 1), which were most successful (most accurate) in predicting rutting failure, indicated by a misclassification error of zero. From the table it is evident that strength, composition, and surface condition of the pavement are the primary factors causing rutting failure for the dataset examined. These results correlate well with the rutting failure chart, given the individual parameters of each factor group, such as “Thin pavement layers” and “Weak materials used”, are also present in FIGURE 2. This result shows it to be advantageous to include such an understanding of failure or knowledge into the early stages of model development to improve on the predictive results of any model.

TABLE 2 also shows the two most unsuccessful factor combinations in predicting rutting failure on the LTPP State Highway road network (i.e. those with the highest misclassification error). These combinations are surface condition (Trial 5) and surface condition and sensitivity (Trial 21); therefore relying on the surface condition of the pavement alone to predict or indicate the potential of rutting failure occurring will not generate reliable outputs, yet many road asset managers base the maintenance of their road networks on the condition of the pavements alone (Schlotjes et al., 2011; Stevens et al., 2009). While the condition data can be used as a good indicator of the severity and speed of the deterioration, it is not suggested to be used solely as an indicator of the cause(s) of failure and maintenance treatment.

The modelling results, for practitioners, can be used together with the failure charts developed (FIGURE 2) to diagnose the cause(s) of failure. For example, trial 52 in TABLE 2 indicates that composition, strength, environment and surface condition are important parameters in determining rutting failure. Referring to the rutting failure chart, FIGURE 2, the failure path of trial 52 is plastic deformation failure → pavement layer rutting → materials → water ingress. Because trial 52 does not consider the traffic factor, the failure path (which can be superimposed on the failure chart) does not include any of the factors associated with the traffic group, such as “Excessive Strain” or “Excessive Traffic Loading”. The inclusion of the composition factor suggests the rutting in this case occurred in the pavement layers as opposed to the subgrade. Since construction quality was not identified as a factor, the next branch the failure path would take the “materials” branch and then further onto the “water ingress” branch, due to the presence of the environment factor group.

Thus the suggested diagnosis is that the pavement fails due to pavement layer rutting. The cause is from water ingress in the lower layers of the pavement, such as the basecourse layer and not the subgrade. With this information, in addition to the data collected on site, the appropriate maintenance would address the problem of water entering into the lower layers of the pavement.

While it is recognised that the number of independent variables included in the successful trials is large, the purpose of this example was to demonstrate the success rate of models that were developed with the assistance of the failure understanding, as opposed to the robustness of the logistic regression model developed for the purpose of the case study. The number of variables included in the development of the models and alternative modelling techniques used in a similar manner are further discussed in Schlotjes (2013).

Practical Applications

As seen from above, the understanding can be used to assist in diagnosing the cause of failure. The information from this diagnosis can be used to identify direct faults to address the principle causes of failure. It can also be used in pavement management systems to aid with improved cost estimations for future maintenance and recognise any symptomatic problems on the network. The identified causes of failure can assist the asset manager in determining if the pavement problem is a base failure requiring only a mill replacement, or an issue further down in the pavement layers where a full rehab would be required. By recognising symptomatic problems on the network, the asset manager can adjust the current practices in respect to the maintenance and construction of the road pavements.

CONCLUSIONS

This paper presented a methodology to develop a comprehensive understanding of, and subsequently descriptive fault trees for, structural road pavement failure for flexible, unbound granular pavements. The development process involved using information available in the literature, expert knowledge and pavement condition datasets to develop failure charts for rutting, cracking and shear failure mechanisms. Two New Zealand datasets helped to determine the complex interactions of co-existing failure mechanisms and interrelated failure factors; however the former was considered outside the scope of his paper and is reported in detail in Schlotjes (2013). Experts from the industry were used to inform the process.

The understanding of pavement failure can be further used to infer engineering knowledge into pavement performance models. The benefits of following such an approach were discussed and include expected improvement on the predictive power and performance of purely mechanistic models. For researchers and practitioners, the fault trees can be used to:

- Identify the factors influencing failure and the factors that should be included in the modelling process,
- Recognise the associated failure path, and
- Assist in diagnosing the cause of failure.

A case study using New Zealand LTPP data was presented which demonstrated how the developed failure charts could assist in the selection of appropriate factors to be included in models of pavement failure. For the rutting failure mode examined, the results from the logistic regression models showed that the main contributing factors to rutting failure were strength, composition, and surface condition of the pavement, and these findings correlate well to the knowledge presented on the rutting failure chart. The unsuccessful trials demonstrated that the sole use of condition data is not reliable in predicting rutting failure.

Adopting an holistic approach to pavement management will likely improve the development of future pavement deterioration models and shift the focus of current asset management practices to incorporate engineering knowledge with computational techniques, so that the most appropriate forecasted maintenance programmes can be determined more accurately. Furthermore, identifying the cause(s) of failure in the manner described will also improve the selection of the most appropriate treatments for individual sites at the project level, and identifying potential symptomatic problems across entire networks.

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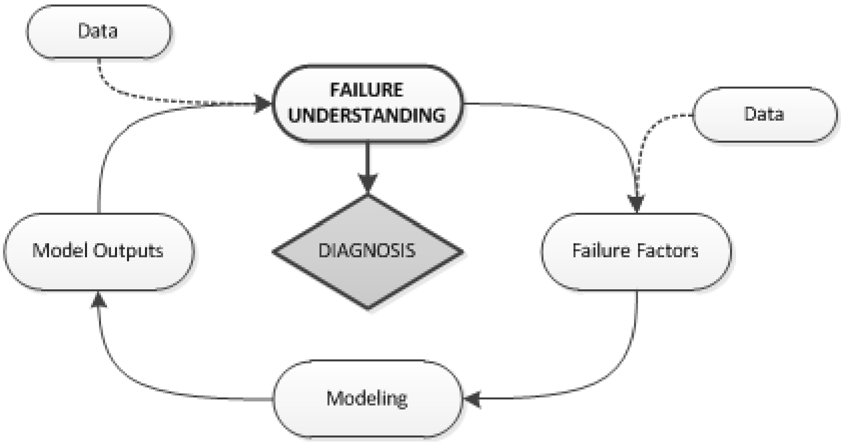

FIGURE 1: Employing the failure understanding

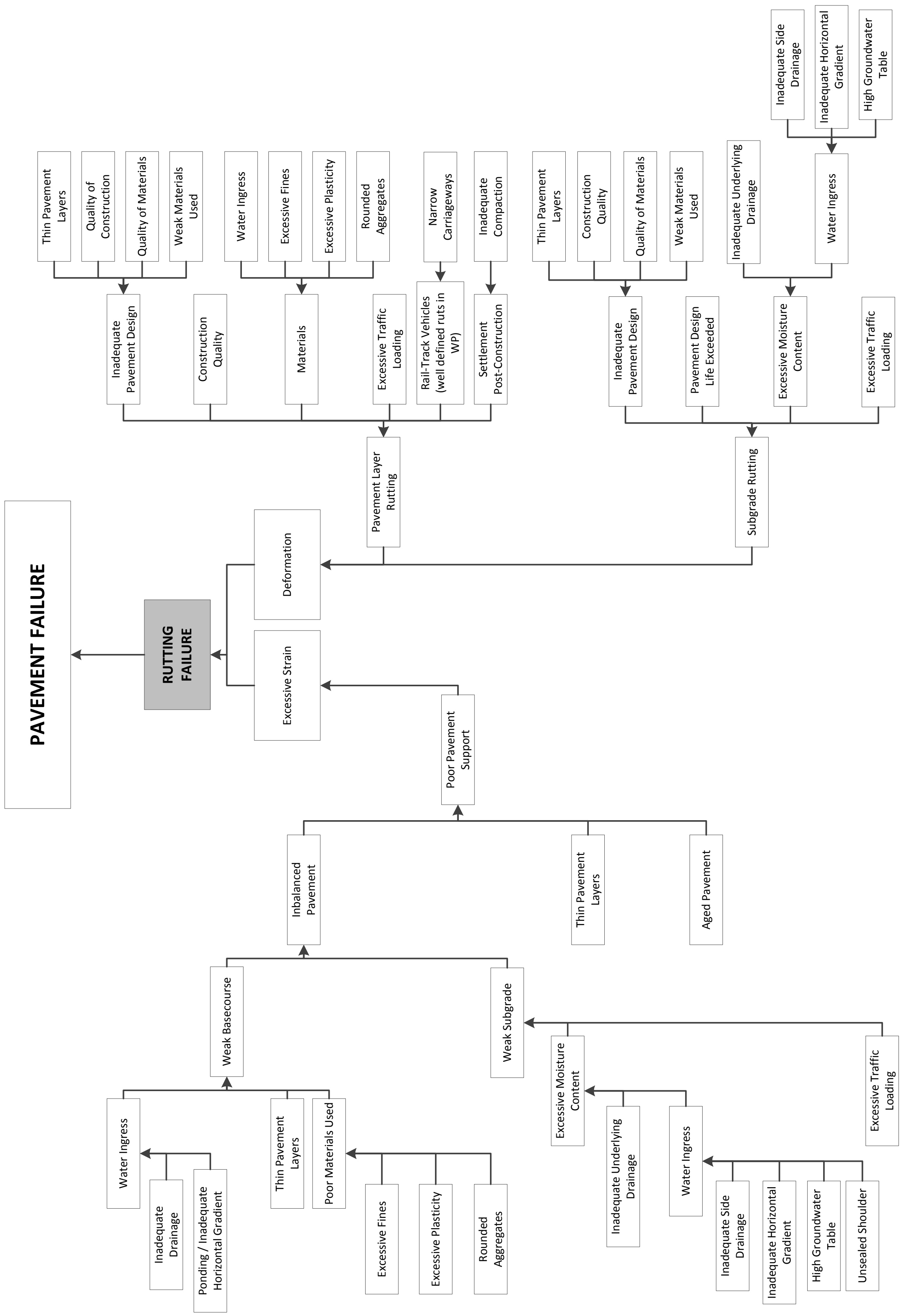

FIGURE 2: Rutting Failure Mechanism Tree (Schlotjes, 2013)

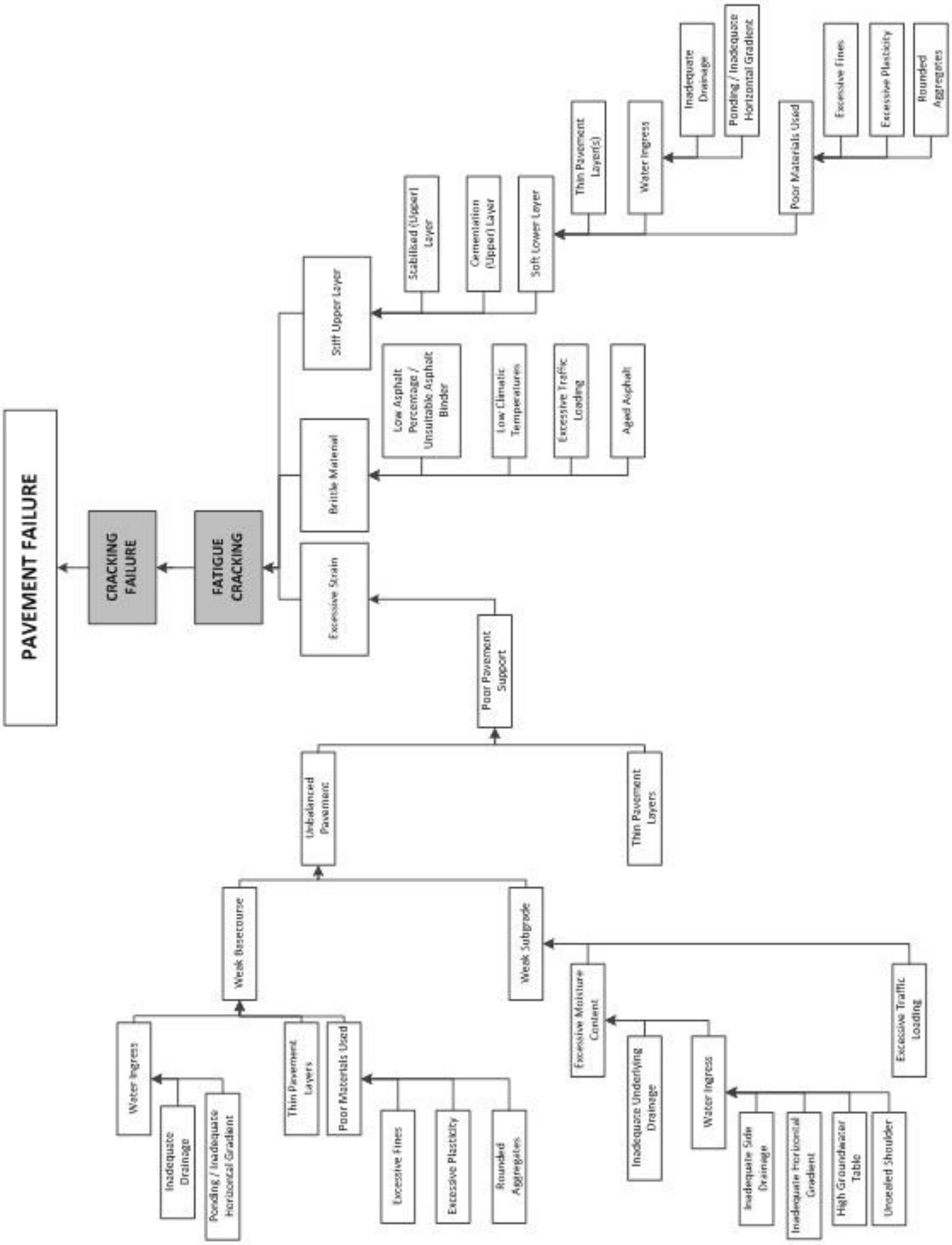

FIGURE 3: Load Associated (Fatigue) Cracking Failure Mechanism Tree (Schlotjes, 2013)

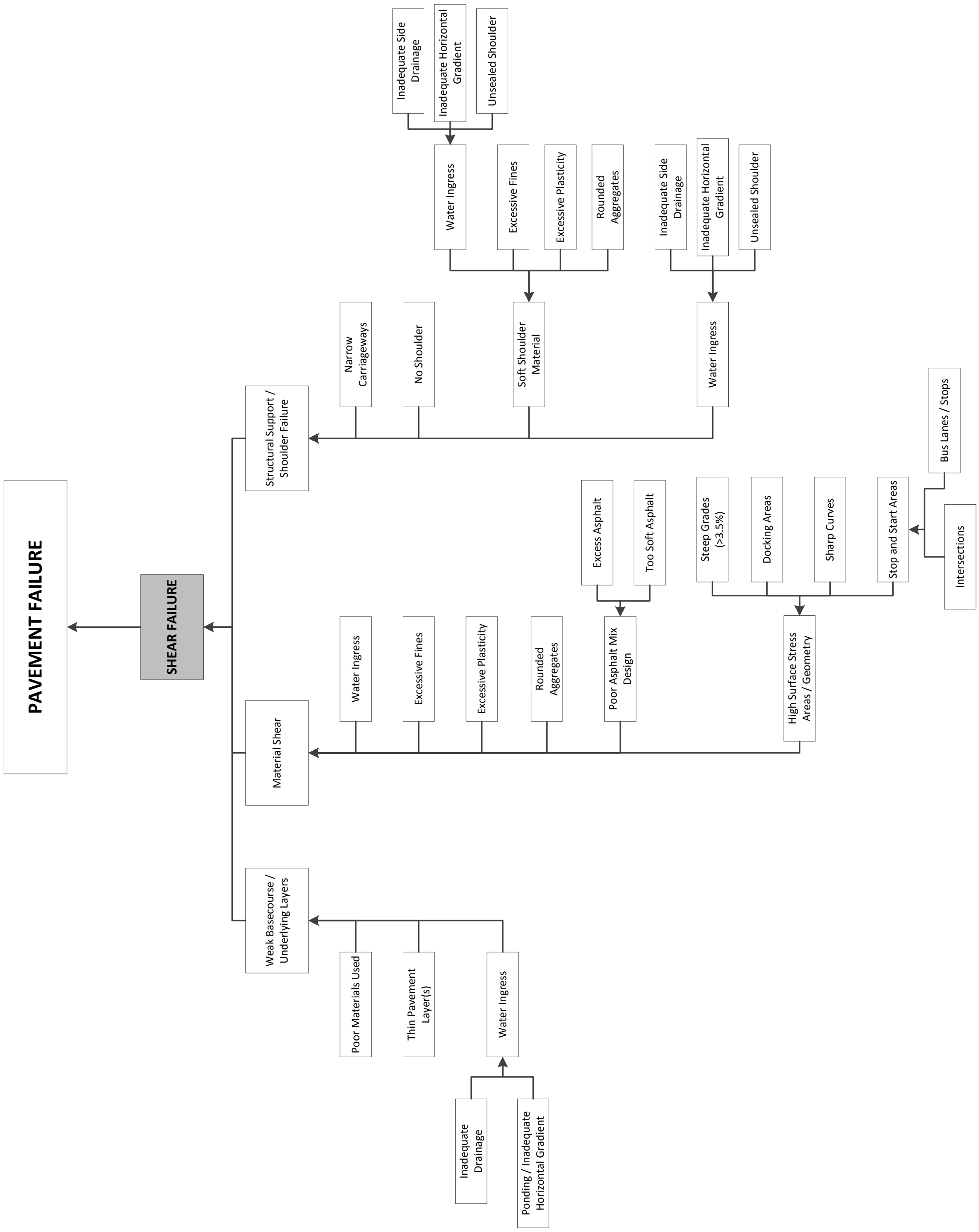

FIGURE 4: Shear Failure Mechanism Tree (Schlotjes, 2013)

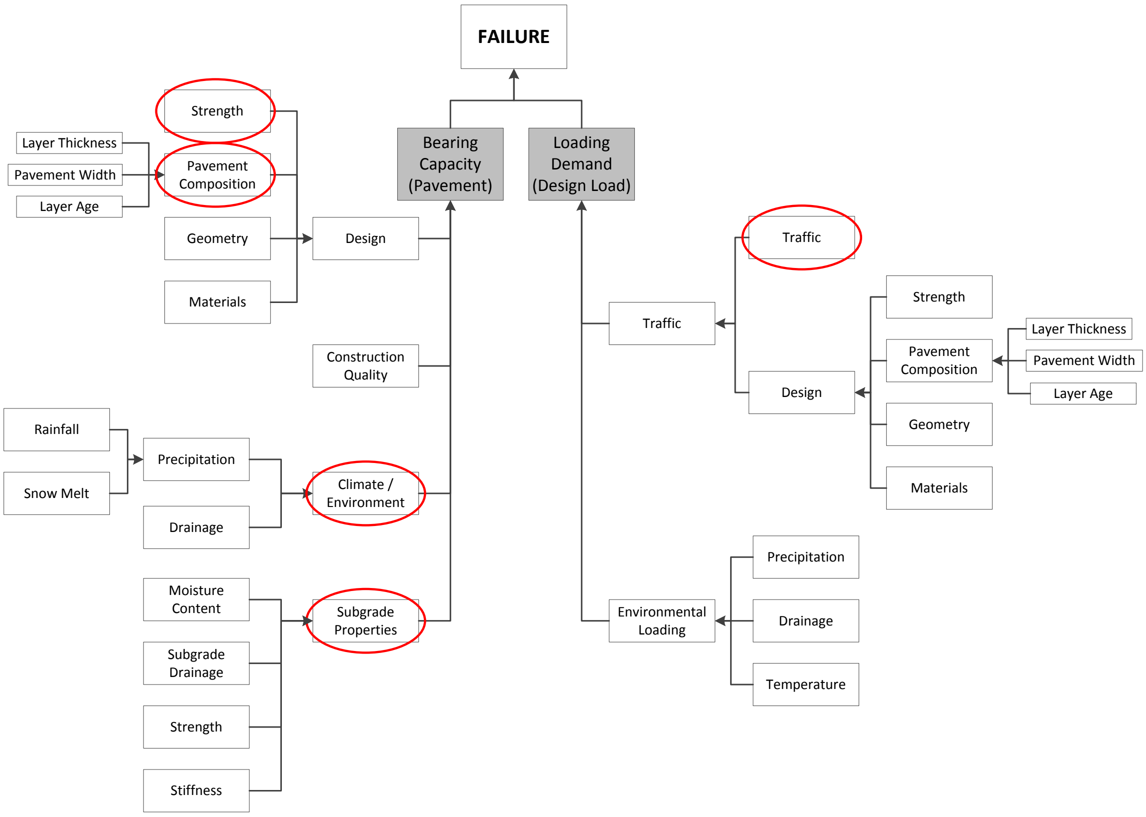

FIGURE 5: Contributing factors to pavement failure

TABLE 1: Major factors associated with flexible pavement failure

FACTOR GROUPS	DESCRIPTION
Traffic	The purpose of a road pavement is to transport goods and people, and to achieve this it is built to withstand traffic loading for a predetermined period of time. However, overloading can cause early failure. Measures of traffic considered are the annual average daily traffic (AADT), percentage of heavy commercial vehicles (HCVs), and cumulative number of equivalent standard axles (ESAs).
Composition	The composition of a road pavement can indicate its expected performance under a particular loading regime. Information about the composition can also help identify under-designed pavements, older pavements, and those which may have exceeded their design life. Factors in this group include pavement age, width, layer thicknesses, and construction materials.
Strength	The bearing strength of the pavement is an important measure of road pavement performance. A weak pavement will not be able to perform sufficiently if under-designed for the given traffic loadings. It also becomes susceptible to early failure. The strength of the pavement is measured in terms of deflection bowls (FWD) and structural number (SNP).
Environment	The climate can damage a pavement significantly. Rainfall, weathering, and temperature can have detrimental effects on the performance of the pavement. Water entering the pavement compromises its structural integrity. High temperatures affect the performance of the bituminous layer(s) and low temperatures can result in freeze-thaw. The change in the temperature gradient reduces the function of the bituminous layer of providing a water-tight layer. Annual rainfall and seasonal temperatures are recorded for this group.
Surface Condition	The current condition of the pavement can give an indication on the type of failure, how advanced the failure is, and the rate of progression of the failure. However, there are some cases where the condition data is a secondary defect to the primary cause of failure; for example, severe rutting can also result in pavement surface cracking, yet the primary cause of failure is the rutting. Condition data differs per failure mechanism, but some examples include rut depths, rut progression rates, amount of cracking, type of cracking, pothole depth and diameter, and number of edge breaks.
Subgrade Sensitivity	The subgrade is the underlying base of the pavement and is protected by the pavement from excessive damage. The susceptibility of the subgrade to damage is primarily a function of its strength, stiffness, and moisture content.

TABLE 2: Results of Logistic Regression Models for Rutting Failure (Schlotjes et al., 2011)

Trial Number	RUTTING FAILURE Factor Combinations	Misclassification Error (%)	No. of Data Points
33	C + S + SC	0	4512
40	S + SC + SS	0	4512
43	T + C + S + SC	0	4512
52	C + S + E + SC	0	4512
54	C + S + SC + SS	0	4512
56	S + E + SC + SS	0	4512
57	T + C + S + E + SC	0	4512
59	T + C + S + SC + SS	0	4512
62	C + S + E + SC + SS	0	4512
63	T + C + S + E + SC + SS	0	4512
5	SC	41.7	4512
21	SC + SS	40.2	4512

T=Traffic; C=Composition; S=Strength; E=Environment; SC=Surface Condition; SS=Subgrade Sensitivity